YUCCA MOUNTAIN SEISMIC HAZARD ANALYSIS

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ABSTRACT

The probabilistic seismic hazard analysis (PSHA) for Yucca Mountain was developed by the U.S. Department of Energy (DOE) in the late 1990s using a formal expert elicitation or expert judgment process based on recommendations from the Senior Seismic Hazard Analysis Committee (SSHAC). This report documents the development of the DOE PSHA and summarizes some of the supporting evaluations performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA®) staff during the prelicensing period to prepare for the DOE license application review. These activities included development of review tools that could be used to help identify and focus on only those faults in the Yucca Mountain region that could contribute to the seismic hazard, as well as the regional geologic and geophysical studies that provided the staff with an improved understanding of the seismotectonic setting. These regional studies proved significant in evaluating alternative interpretations of the seismic hazard levels at Yucca Mountain based on emergent Global Positioning Satellite (GPS) technologies and related alternative interpretations of the tectonic setting. This document also describes some of the relevant new information and technical developments and updates to the SSHAC process that occurred after DOE completed the PSHA, and during the development of the Yucca Mountain Safety Evaluation Report. These include (i) research carried out by the United States Geological Survey and the CNWRA on the extreme ground motions indicated by the DOE PSHA at low annual exceedance probabilities (AEPs) (less than about 10^{-6}/yr), and (ii) the significant developments in how the SSHAC principles are administered based on lessons learned from many recent applications of the SSHAC process used to update the seismic hazards at U.S. nuclear power plants following the 2011 Great Tohoku earthquake and resulting disaster at the Fukushima Dai-ichi nuclear power plant.

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QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: All CNWRA-generated data contained in this report meet quality assurance requirements described in the CNWRA Quality Assurance Manual. Sources of other data should be consulted for determining the level of quality of those data. No original data were generated in this report.

1 INTRODUCTION

1.1 Background

The proposed high-level radioactive waste repository site at Yucca Mountain, Nevada, is located in a region in the western United States with moderately active seismicity (Figure 1-1). The U.S. Department of Energy (DOE) identified seismic hazards as one of the credible natural hazards that could adversely impact the proposed Yucca Mountain site. DOE concluded that an accurate assessment of the seismic hazard at the site was needed for the design and safety analysis of the surface facilities during the preclosure period,[1] and the performance assessment of the repository for the postclosure period.[2] During the 1980s and 1990s, DOE supported extensive geological, geophysical, and seismological studies by the United States Geological Survey (USGS), Bureau of Reclamation, the DOE National Labs, and other contractors that were used as part of its seismic hazard analysis.

As stated in the DOE license application, the proposed geologic repository would be configured to dispose up to 70,000 MTHM (Metric Tons of Heavy Metal) of high-level radioactive waste and spent nuclear fuel in underground horizontal drifts that are situated approximately 300 m below the ground surface. To emplace this material underground, DOE proposed a design that included waste handling facilities, a network of roads and rail for surface transportation of waste among the surface facilities, flood control structures, and related support systems. The waste handling facilities would include initial waste receipt, canister transfer, thermal aging, wet and dry handling, and underground emplacement. DOE proposed to construct these surface facility installations above a thick sequence of alluvium and tuff in Midway Valley, which is located just east of the potential repository footprint within Yucca Mountain (Figure 1-2).

DOE's overall approach to developing a seismic hazard assessment for Yucca Mountain involved the following two steps. In the first step, DOE conducted an expert elicitation in the late 1990s to develop a probabilistic seismic hazard analysis (PSHA) for Yucca Mountain (CRWMS M&O, 1998). The PSHA was developed for a reference bedrock outcrop, specified as a free-field site condition with a mean shear wave velocity (V_S) of 1,900 m/s and located adjacent to Yucca Mountain. This value was derived from a V_S profile of Yucca Mountain with the top 300 m of tuff and alluvium removed, as provided in Schneider et al. (1996).

In the second step, DOE conducted site-response modeling to condition the PSHA results so they would be applicable to the surface facilities in Midway Valley and the repository drifts in the subsurface (BSC, 2004). Site response modeling accounts for changes in seismic energy (amplification or deamplification, attenuation, and damping) as the seismic waves propagate through the tuff layers in the repository strata directly beneath the proposed emplacement drifts and in the layers of soil and alluvium directly beneath the proposed surface facilities in Midway Valley (Figure 1-2). DOE relied on the resulting repository-level and surface-level seismic hazard curves as inputs to its postclosure performance assessment, surface and subsurface design, and preclosure seismic risk assessment used to evaluate the likelihood of accident event sequences initiated by earthquakes.

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[1] The preclosure period (period of operations) includes (i) the time during which emplacement would occur, (ii) any subsequent period before permanent closure during which the emplaced wastes are retrievable, and (iii) permanent closure.

[2] The postclosure period is the period following permanent closure of the repository through the period of geologic stability.

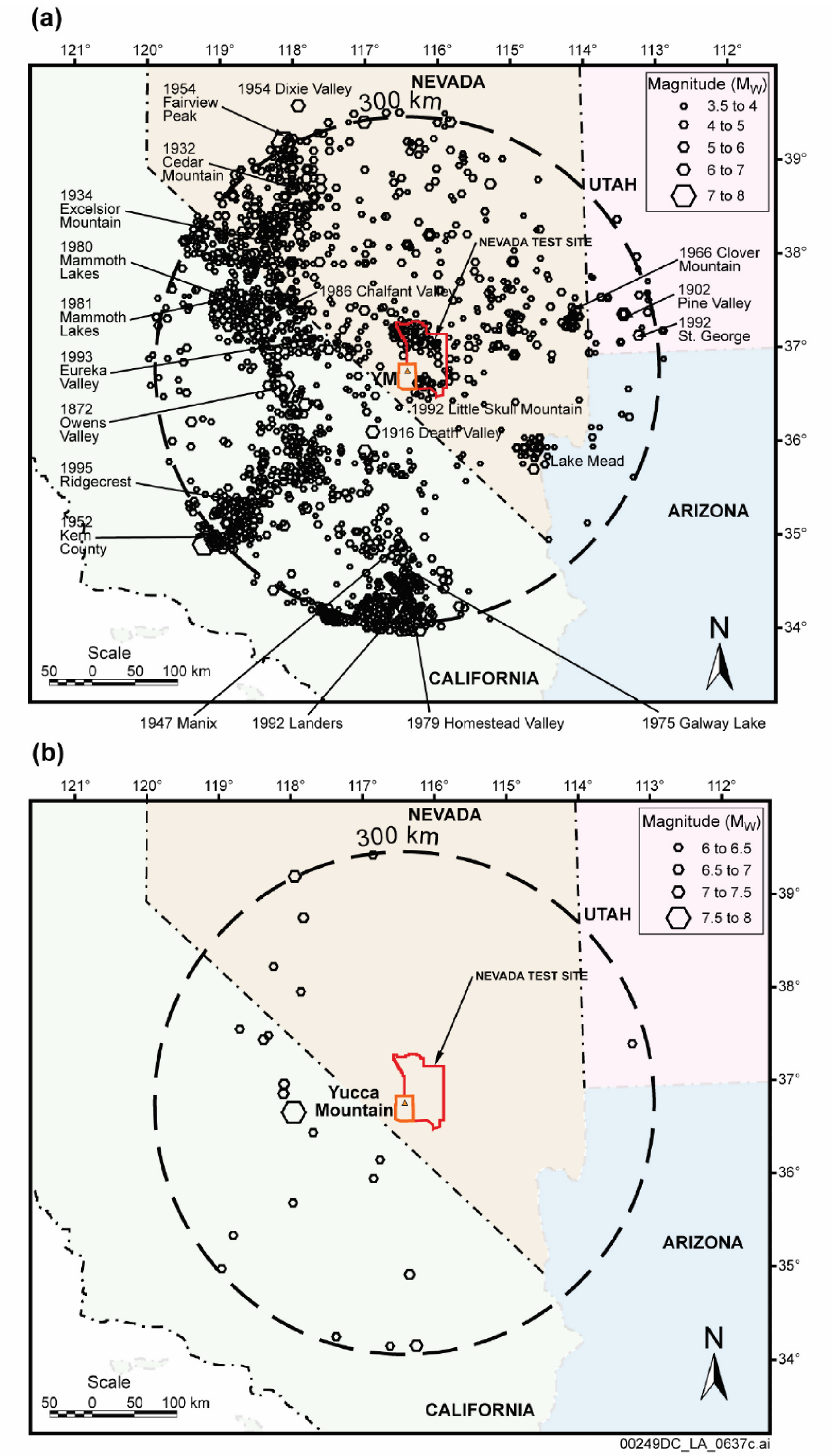

Figure 1-1. Earthquakes recorded within 300 km of the Yucca Mountain region from 1886 through 1996 with moment magnitude (M_W) greater than 3.0 shown in (a) and Mw≥6.0 shown in (b). This figure was adapted from Figure 1.1-68 of DOE (2008).

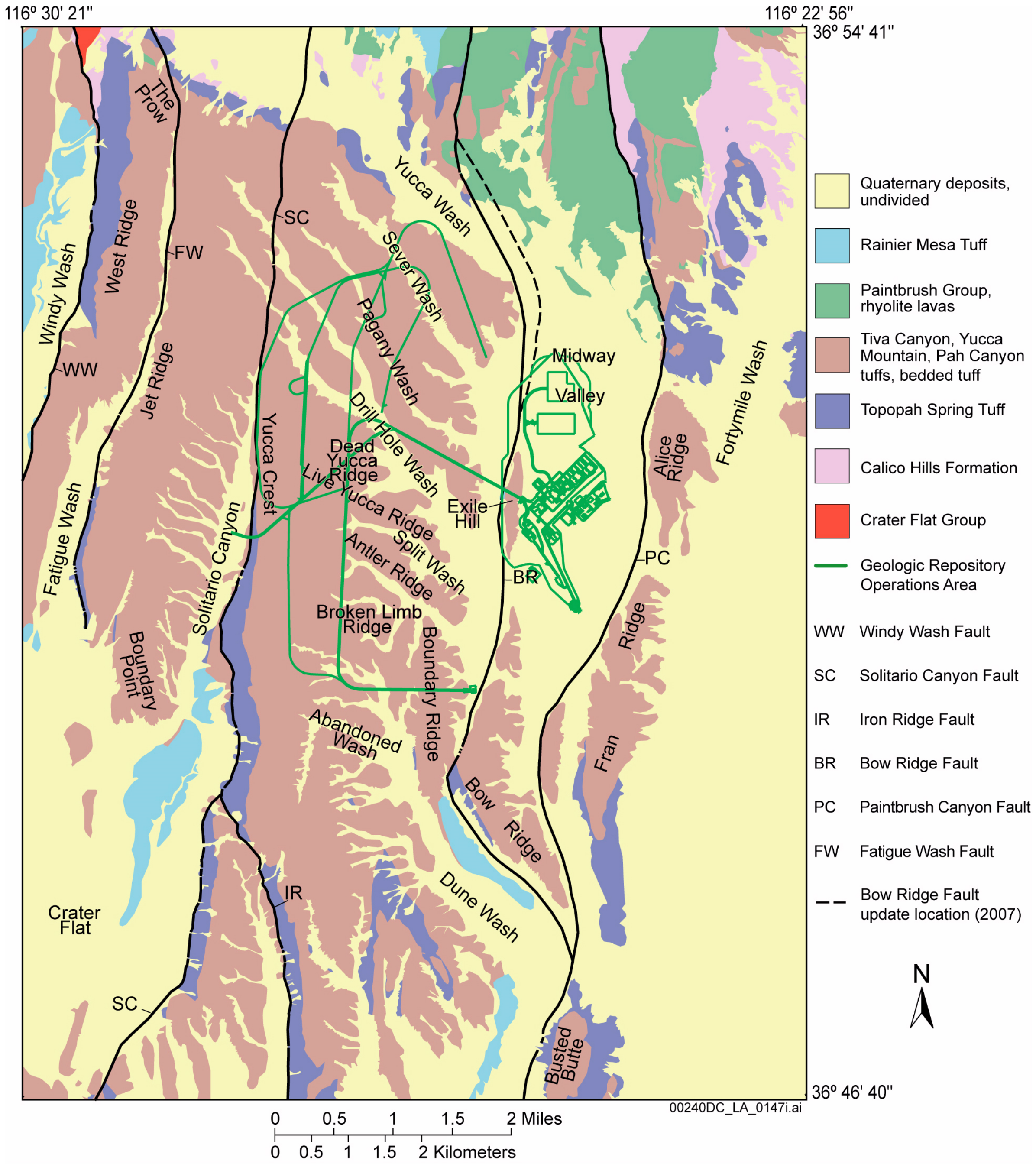

Figure 1-2. Generalized geologic map of Yucca Mountain repository area. The green lines depict the location of the proposed surface facilities. This figure was adapted from Figure 1.1-59 of DOE (2008).

1.2 Objective and Scope

This report focuses on the first of the two steps DOE used to develop a seismic hazard assessment for Yucca Mountain: the development of the DOE PSHA and some of the supporting studies that the Center for Nuclear Waste Regulatory Analyses (CNWRA®) and U.S. Nuclear Regulatory Commission (NRC) staffs conducted in preparing for the review of the DOE license application. This report also describes some of the relevant new information and technical developments that accrued during the development of the Safety Evaluation Report (SER), after DOE submitted its license application in 2008. The second step involving the site response analysis will be described in a separate report. Chapter 2 of this report summarizes the DOE PSHA conducted in the 1990s. Chapter 3 describes some of the supporting studies carried out by the CNWRA and NRC staffs as part of activities preparatory to reviewing the DOE license application. Chapter 4 describes the advances in seismological research and expert judgment procedures that occurred after DOE submitted its 2008 license application, during the development of the SER. This includes new information on how to characterize very low-probability ground motions. Chapter 5 gives a brief summary and Chapter 6 documents the references cited in the report. Although the purpose of the report is to convey the thought process and independent analyses conducted as part of the Yucca Mountain license application review and describe the preparatory studies for the Yucca Mountain license application review, information presented in this report also may be of interest to other safety analyses and reviews involving seismic hazards.

2 DOE PROBABILISTIC SEISMIC HAZARD ANALYSIS

DOE calculations of the seismic hazards for both preclosure and postclosure analyses in the Yucca Mountain license application were developed from a PSHA conducted by DOE in the late 1990s (CRWMS M&O, 1998). Because of the complexity in the tectonic environments at Yucca Mountain and the limited data available for seismic source and ground motion characterization, DOE utilized an expert elicitation process for the PSHA. This expert elicitation process was based on two sets of formal guidance being developed at that time. In 1996, the staff within the NRC Division of Waste Management published guidance in NUREG–1563 (NRC, 1996) describing acceptable procedures for conducting expert elicitation when formally elicited judgments are used to support a demonstration of compliance with NRC's geologic disposal regulations. DOE also implemented the more extensive expert elicitation guidance that was being developed concurrently by the Senior Seismic Hazard Analysis Committee (SSHAC). The SSHAC recommendations were subsequently published in NUREG/CR-6372 (Budnitz et al., 1997).

The motivation to establish the SSHAC arose because of the significant differences in the seismic hazard results from two landmark studies that were conducted in the late 1980's to evaluate seismic hazards at nuclear facilities in the central and eastern United States. The Electric Power Research Institute-Seismicity Owners Group (EPRI-SOG, 1988, 1989) and Lawrence Livermore National Laboratory (LLNL) (Bernreuter et al., 1989) studies were both conducted using multiple experts, and both studies were mindful of the importance of uncertainties. Yet, the results of the two studies differed both in terms of the assessments of individual experts within each study and in the mean hazard results between the two studies. The two studies produced an order of magnitude difference in the resulting seismic hazard over the range of annual exceedance probabilities (AEPs) that is most germane to seismic risk evaluations for nuclear power plants (10^{-4} to 10^{-6}).

In brief, SSHAC is a structured process to develop probabilistic hazard analyses based on objective and comprehensive evaluation of available information in the technical community, integration of that information into appropriate hazard component models, robust participatory technical review throughout the study, and transparent and complete documentation of all components and decision-making. SSHAC defines four study levels (Level 1 through Level 4), each with increased complexity, technical rigor, and cost. The higher the SSHAC level, the greater the likelihood that the resulting hazard captures what in the SSHAC lexicon is known as the center, body, and range of technically defensible interpretations; thereby increasing the regulatory assurance provided by the study. Because of the potential radiological risks from nuclear facilities, the committee recommended that only Level 3 or Level 4 studies be used for such facilities. Although the DOE PSHA study began before NRC's NUREG/CR-6372 guidelines document was published, the DOE PSHA was accomplished as a SSHAC Level 4 study.

The DOE PSHA consisted of two components: a seismic source characterization and a ground motion characterization. These components of the PSHA are briefly described in the next two sections of this report. The full description of the DOE PSHA is in CRWMS M&O (1998). A summary of the DOE PSHA also was published in the earthquake engineering literature by Stepp et al. (2001).

One of the fundamental properties of an SSHAC study is the use of the Participatory Peer Review Panel (PPRP). Indeed, DOE's choice to use an SSHAC study for Yucca Mountain was based on the realization that the current set of data, models, and methods used to assess seismic hazards included substantial complexity and uncertainty such that a detailed evaluation and integration by technical experts was needed, including a large degree of their expert judgment. The SSHAC process was designed to develop reliable and robust estimates of seismic hazard in the absence of technical certainty, and to capture the center, body, and range of technically defensible interpretations as a means to developing best estimates probabilistically. Confirmation that the center, body, and range have been captured only comes from the fidelity of the SSHAC assessment process itself and the endorsement from the PPRP that the project adhered to the principles of the SSHAC process. The PPRP for the Yucca Mountain study comprised four well-known senior seismologists and seismic engineers. In giving its endorsement, the PPRP assured stakeholders that, in their opinion and based on their participatory review, all the relevant information was considered and evaluated, that the varied proponent interpretations were heard and objectively considered, that all decisions were arrived at based on technically defensible interpretations, and that the entire process was clearly documented and defended.

2.1 Seismic Source Characterization

For the seismic source characterization, six teams of experts developed a probabilistic model of future earthquake generation in the Yucca Mountain region that could impact the site. Each of the six teams included experts in paleoseismology, Basin and Range structural geology, and Basin and Range seismology. For their assessments, the six teams evaluated and integrated available geological, geophysical, and seismological information provided by DOE-sponsored studies that were carried out by the USGS and the U.S. Bureau of Reclamation; DOE project-specific Yucca Mountain studies; and published geological, geophysical, and seismological literature. The teams met at six workshops held between April 1995 and June 1997, during which the experts exchanged information on seismic sources and participated in additional discussions with other subject matter experts, especially experts who had published proponent models of potential earthquake sources. One of the workshops included a field trip to the Yucca Mountain vicinity to observe many of the relevant geological features.

The approach used by the expert teams to characterize potential seismic sources followed standard practice for seismic hazard assessments of sites west of the Mississippi River, where better exposure of bedrock and greater tectonic activity make identification of fault sources easier to discern. In this seismic source characterization, fault sources are used in hazard assessments to account for expected seismicity on known or suspected fault traces. Uncertainty in fault sources is accounted for by alternative interpretations of fault length, fault dip, closest approach to the Yucca Mountain site, depth within the seismogenic crust, and possible kinematic linkage with other faults. In the probabilistic seismic hazard analysis calculations, earthquakes are assumed to occur randomly along the fault surface, constrained by the size of the fault rupture area.

The expert teams also developed areal sources to account for distributed or background seismicity for which there is limited or no geologic or geophysical evidence that can tie past earthquakes to known faults. In this way, areal sources account for earthquakes that occur on unidentified or unidentifiable fault sources. Areal sources typically are developed to represent earthquakes with magnitudes that may not necessarily cause surface rupture. The boundaries of areal sources are drawn to define areas with relatively uniform seismicity and maximum magnitude, generally defined by the historic seismic record. To quantify the historical seismicity of the region, the DOE facilitation team developed a single earthquake catalog that was compiled from 12 regional catalogs.

The seismic source characterization model was based on a standard logic tree used to delineate the alternative interpretations into a coherent framework and to incorporate uncertainty. The first branch of the tree identified the likelihood of fault activity based on different interpretations of local and regional tectonics derived from the suite of viable tectonic models. Subsequent branches evaluated alternatives in fault-specific characteristics, such as fault linkage, segmentation, maximum magnitude, activity rate, and seismogenic depth. Uncertainty in the source characterization was accounted for by assigning expert-generated weights to the branches of the logic tree (i.e., uncertainty attributable to incomplete knowledge about a phenomenon). Because the DOE PSHA was essentially a Level-4 SSHAC study, each of the six expert teams developed their own seismic source logic tree to reflect their view of the distribution that captures the seismic source characterizations, including uncertainty. The Technical Facilitator Integrator for the SSHAC study then combined the six logic trees with equal weighting into a single overall logic tree. This logic tree represents the expert teams' combined interpretation of the size, location, and frequency of future seismicity generated by fault and areal sources at Yucca Mountain.

2.2 Ground Motion Characterization

For the ground motion characterization, seven individual experts participated in the PSHA. These experts relied on information provided by the USGS; DOE; other project-specific Yucca Mountain studies; and published geological, geophysical, and seismological literature. All seven experts participated in three workshops, two working meetings, and a one-day elicitation meeting. These meetings were held between April 1995 and June 1997, during which the experts exchanged information on ground motion attenuation and participated in additional discussions with other external experts.

The experts provided estimates of the level of ground motion at the Yucca Mountain site (including aleatory variability and epistemic uncertainty) for a large matrix of seismic source conditions (source-to-site distance, focal depth, faulting type, and magnitude). These estimates were based on empirical and numerical simulation-based models and combinations of conversion factors to account for differences in the crustal conditions at Yucca Mountain compared to the crustal conditions where the earthquake strong motion records were obtained (mainly California). The result was that each expert characterized the resulting ground motion for each of the earthquake source conditions in the matrix by four values: (i) the median ground motion, (ii) the aleatory standard deviation of the median, (iii) the epistemic uncertainty for the median values, and (iv) the epistemic uncertainty in the aleatory variability. The ground motion experts' point estimates of the ground motion were parameterized by the ground motion Technical Facilitator Integrator as attenuation equations for use in the hazard calculations. The Technical Facilitator Integrator developed the ground motion attenuation equation to best fit each expert's input values, but the equations for all seven experts had the same functional form. Each of the resulting seven attenuation equations formed a branch in the ground motion logic tree. Similar to the seismic source characterization, the seven ground motion branches were then combined into a single logic tree, giving equal weight to each branch. The resulting ground motion logic tree represents the expert teams' combined interpretation of the amplitudes of ground shaking that will occur at the reference bedrock outcrop given the seismic source model as input. The uncertainty captured by these seven individual attenuation relations (individual branches in the final ground motion logic tree) captured the epistemic uncertainty of the ground motion characterization.

2.3 PSHA Results

DOE calculated PSHA results for Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), and spectral accelerations at 0.3, 0.5, 1, 2, 5, 10, and 20 Hz structural frequencies. Deaggregation of the hazard showed that PGA and the 5-20 Hz spectral accelerations were largely controlled by nearby earthquake sources (less than 15 km away from the Yucca Mountain site) producing earthquakes with a Moment Magnitude (**M**) of 6.5 or less. In the resulting PSHA, the most likely contributing sources for these earthquakes were the host areal seismic source zone and the Paintbrush Canyon, Iron Ridge, and Solitario Canyon faults. At lower frequencies, in the range of 1-2 Hz, the ground motions were dominated by larger events (**M** > 7.0) from sources beyond 50 km. The most likely contributors to the low frequency hazard were the Death Valley and Furnace Creek faults. In general, the greatest contributors to uncertainty in the hazard were within-individual experts' calculated uncertainty, rather than expert-to-expert uncertainty. Additionally, the total uncertainty caused by ground motion was larger than the uncertainty caused by the seismic source characterization.

Results of the PSHA were presented in the form of summary hazard curves (Figure 2-1), which depicted the mean, median, and the 15th and 85th fractiles of the calculated hazard curves. The mean and median show the central tendency of the hazard results while the separation between the 15th and 85th fractile curves shows the epistemic uncertainty on the calculated exceedance frequency. Figure 2-1 is for PGA and the 1 Hz spectral frequency. Similar curves were developed for all the spectral accelerations and PGV. Based on this curve, the rock PGA at an AEP of 10^{-4} is approximately 0.7g. At AEPs below 10^{-6}, the mean values exceeded 3g, and at 10^{-8} AEP, the PGA exceeded 10g. As noted in the introduction to this report, these results were for the reference bedrock outcrop conditions and had to be conditioned by the site response to be applicable to the surface facilities in Midway Valley or the repository horizon in the subsurface.

2.4 CNWRA Supporting Evaluations

Staff from the NRC and CNWRA focused on three aspects of the DOE study to support the regulatory and technical review of the DOE PSHA. First and foremost, staff from the NRC and CNWRA observed all aspects of the SSHAC expert elicitation by attending all the workshops and associated field trips, and staff observed that DOE followed all the essential procedural requirements necessary to successfully complete the SSHAC Level 4 study. A more detailed summary evaluation of the DOE PSHA by the NRC staff is available in Section 7.4.4.2 of NUREG–1762 (NRC, 2005).

Second, staff independently developed a catalog of all known faults within a 100 km radius of Yucca Mountain and categorized these faults according to their potential to affect repository design, safety, or performance (McKague et al., 1996). This catalog was developed through literature review, detailed analysis of published geologic maps, geographic information systems analysis of digital topography and satellite imagery, and field surveys. The purpose of the catalog was to develop a performance based and risk-informed approach to fault characterization in order to assist the NRC staff with its technical review of the DOE fault characterization activities. The categorization followed the framework for fault identification developed in NUREG−1451 (NRC, 1992). Those faults that were potentially significant to the seismic source characterization in the PSHA, based on a set of fault characterization criteria (e.g., age of displacement, location, length, associated historic seismicity, orientation within the

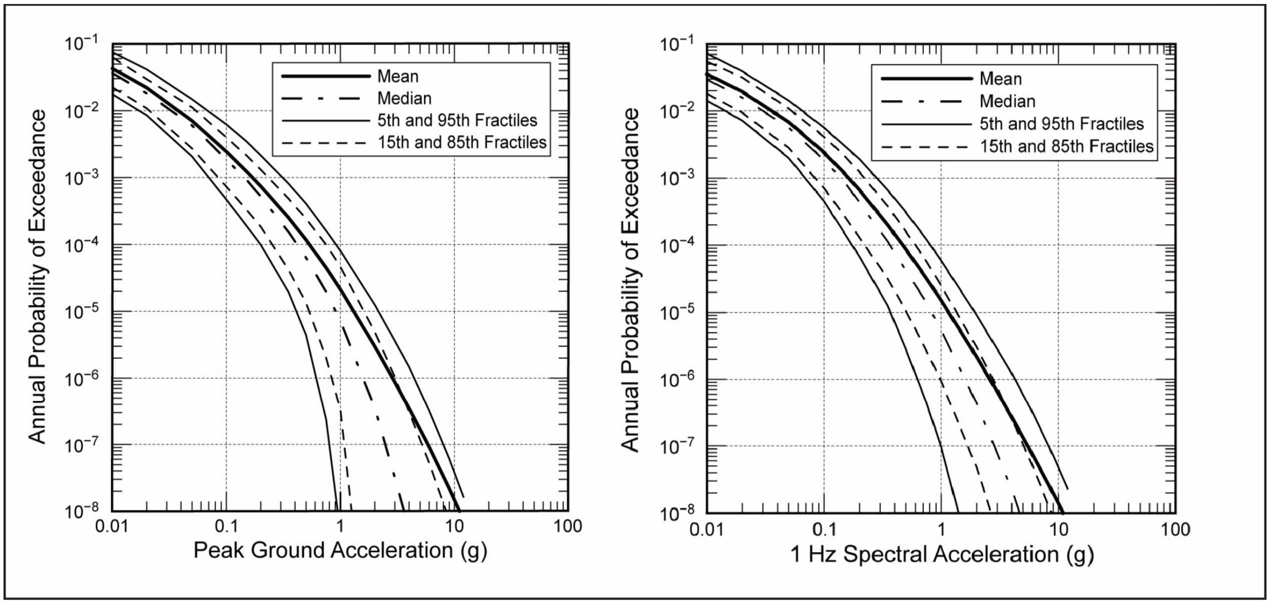

Figure 2-1. Hazard curves at the reference bedrock rock outcrop for peak horizontal ground acceleration and 1 Hz horizontal spectral acceleration. This figure was adapted from Figure 1.1-74 of DOE (2008).

present crustal stress field), were classified as “Type I faults.” Of the more than 400 faults identified within a 100 km radius of Yucca Mountain, 52 were Type I faults.

This characterization of faults compared favorably to many of the DOE supporting studies conducted by the USGS and the U.S. Bureau of Reclamation. The Type I fault tabulation in McKague (1996) also compared favorably with a similar catalog of faults developed by the USGS (Piety, 1996). This USGS catalog defined the initial set of faults that was evaluated by the six expert teams in the seismic source characterization of the DOE PSHA. Development of the independent catalog improved the CNWRA staff’s understanding of the quality and applicability of the USGS and U.S. Bureau of Reclamation data used to support the fault source characterization in the DOE PSHA. One of the key contributions made by the CNWRA for this study was the development and application of a fault stress analysis code called 3DStress® (Morris et al., 1996). This code allowed users to identify those faults with favorable orientations for future rupture within the current crustal stress field and those with an orientation suggesting that they are locked and less capable of fault slip in the near future.

Third, during the prelicensing period, the staff investigated the geological and geophysics of the region surrounding Yucca Mountain to gain a fundamental understanding of the geological history of the region and the present-day seismotectonic setting. This understanding provided the NRC and CNWRA scientists and engineers with the necessary technical expertise to critically evaluate whether the DOE PSHA inputs on seismicity, seismicity rates and recurrence, and faults and faulting activity were consistent with the regional geology. Detailed descriptions of this work can be found in Ferrill et al. (1995) and Stamatakos et al. (2000). This work included structural geologic mapping in Crater Flat and on Bare Mountain, 2D and 3D structural restorations, analog sand-box modeling of strike-slip and normal fault systems, ground-based geophysical investigations (magnetic anomaly mapping, gravity measurements, and magnetotellurics), paleomagnetic studies, and radiometric dating of geologic materials. Collectively, these studies formed the bases for the development an integrated and comprehensive interpretation of the geological evolution of the Crater Flat basin and Bare Mountain, which is described in Stamatakos et al. (2000).

The value of these above-mentioned regional tectonic studies was evident several times during the prelicensing period, especially when alternative and controversial results arose in the scientific community. For example, Wernicke et al. (1998) suggested that strain rates across Yucca Mountain were at least an order of magnitude higher than strain rates derived from DOE-sponsored Quaternary fault studies. The Wernicke et al. (1998) results were based on campaign-style Global Position Satellite (GPS) measurements, which was a new and emerging technology at that time. These GPS rates were used to determine the relative motions of the various fault-bounded crustal blocks, and thus, to infer fault slip rates used in the seismic source characterization of the PSHA. The Wernicke et al. (1998) GPS results created significant controversy among the larger technical community and the public because they challenged the many years of more traditional geologic results on the faults near Yucca Mountain.

However, based on an understanding of the geology of the region, the NRC and CNWRA staffs determined that these GPS results were incongruous with the tectonic setting of the region, and were therefore in error. The high rates of crustal extension proposed by Wernicke et al. (1998) would manifest as Quaternary and even Holocene-aged landforms (e.g., fault scarps, truncated alluvial fans, push-up ridges) that are not present in the Yucca Mountain region. In contrast, detailed geological and geophysical investigations described in Stamatakos et al. (2000) showed that the existing fault block landscape had developed during a period of relatively rapid extensional faulting and basin growth during the Miocene. Fault slip rates on the Bare Mountain fault (the largest capable fault within 20 km of Yucca Mountain) during the period of rapid extension in the Miocene was nearly 100 times greater than current slip rates: approximately 1–3 mm/yr in the Miocene compared to the present-day rate based on Quaternary faulting studies of 0.01 mm/yr (Anderson and Klinger, 1996) or 0.03 mm/yr based on the burial of a 1 Ma lava flow near the Little Cones volcano in southern Crater Flat (Stamatakos et al., 1997). Slip rates of 0.03 mm/yr or less on these faults also was consistent with the rates relied on by the technical experts in the DOE SSHAC study.

This type of knowledge of the regional geology gained from the years of technical activity enabled the NRC and CNWRA staffs to effectively evaluate the initial Wernicke et al. (1998) results. The PSHA seismic source experts were also skeptical when these GPS results were vetted through the SSHAC process. The Wernicke et al (1998) model was presented to the seismic source experts as a proponent model during one of the SSHAC workshops. However, these seismic source experts came to a similar conclusion to the CNWRA and NRC staffs about how unreliable the Wernicke (1998) GPS measurements were in estimating fault slip rates across Yucca Mountain. Instead, the fault slip rates relied on by the seismic source experts in the PSHA were consistent with the staff’s understanding of the geologic and seismotectonic setting. The skepticism on the part of the experts conducting the SSHAC study and the NRC and CNWRA staffs was eventually substantiated when subsequent and more reliable permanent-station GPS measurements from Wernicke et al. (2004) refuted their 1998 results and reaffirmed the relatively slow strain rates indicated by the geologic data.

3 TECHNICAL DEVELOPMENTS SINCE 2008

Since the DOE PSHA results were published in 1998, and during the time NRC and CNWRA staff were reviewing the DOE license application, several important developments or advancements in technology and methodology occurred that bear on the DOE PSHA results. First, beginning in 2003 and culminating with the publication of an Open File report in 2013 (Hanks et al., 2013), DOE and the USGS conducted a series of technical investigations to evaluate the very large ground motions indicated at low AEPs (less than about 10^{-6}); what later became known as "extreme ground motions." CNWRA staff also investigated these extreme ground motions through a statistical analysis of aftershocks from the 1999 Chi-Chi earthquake. Second, the SSHAC process to use expert judgment in developing seismic hazards has advanced considerably since its application at Yucca Mountain, especially because of its use for reevaluation of seismic hazards at all the nuclear power plants in the U.S. fleet following the events at Fukushima that resulted from the 2011 Tōhoku earthquake and tsunami. Based on lessons learned from the application of SSHAC since 1998, the SSHAC process has been significantly refined and improved. Most germane to the Yucca Mountain PSHA is that current SSHAC guidance includes flow-chart procedures to evaluate whether an existing SSHAC study remains valid in light of new data, models, or methods. In addition, SSHAC guidance also has evolved such that SSHAC Level-3 studies (as opposed to the Level-4 SSHAC used for the 1998 DOE PSHA) can be conducted in a way that provides a similar degree of regulatory assurance as a Level 4 study.

These developments in extreme ground motions and SSHAC process improvements are described further in the following two sections of this report.

3.1 Extreme Ground Motions

As noted in Section 2.3 of this report, the resulting PGAs at Yucca Mountain for the 10^{-6}, 10^{-7}, and 10^{-8} AEPs at the reference bedrock outcrop site are 3g, 6g, and 11g, respectively, and the resulting PGVs for the same AEPs are 3.0 m/s, 6.5 m/s, and 13.0 m/s. These extreme ground motions arise in the PSHA because of the use of unbounded or untruncated lognormal distributions to account for the scatter in the ground motion estimates about the calculated median values. A feature of unbounded lognormal distributions is that, at very small probabilities, extreme values arise because the ground motion models are extrapolated into the tails of their underlying lognormal distributions. Because most PSHA studies prior to the Yucca Mountain study were developed for applications that relied on the hazard result with AEPs in the range of 10^{-3} to 10^{-5}, issues associated with these kinds of large ground motions at very low AEPs had not been of concern.

These very large PGA and PGV values generated considerable questions and concerns within the larger scientific, engineering, and regulatory communities because such large PGVs and PGAs have never been recorded for any earthquakes worldwide, they present exceptional challenges to the design and construction of underground facilities, and they are regarded by most qualified seismologists and geotechnical engineers as physically unrealizable. In response to these questions and concerns, DOE first formed the Extreme Ground Motion Committee, which developed a research plan based on feedback and technical input from the larger scientific community through a series of workshops; principally, the Workshop on Extreme Ground Motions at Yucca Mountain, which was held in Menlo Park, California, August 23–25, 2004. The resulting workshop report established a basic framework for an extreme ground motion research program and led to the research published in Hanks et al. (2013). This USGS extreme ground motion program emphasized three areas of research.

The first area of research was to evaluate the potential for a physical limit to the ground motion based on nonlinear behavior of rock and the geomechanical properties of the near surface volcanic and sedimentary strata at Yucca Mountain. The main focus of this research was to evaluate the level of vibratory ground shaking at which these strata begin to deform in nonlinear and nonelastic ways (e.g., fracturing or irreversible compaction of porosity) that dissipate the seismic energy. Once these rocks reached this threshold and behaved nonlinearly, they would not be able to transmit the excess seismic energy above the threshold to the surface or the repository level. Andrews et al. (2007) first modeled these thresholds of ultimate strength in the volcanic and sedimentary material using an extreme event on the Solitario Canyon fault. Results of his models, as presented in Hanks et al. (2013), indicated a maximum horizontal PGV between approximately 3.0 and 6.0 m/s, depending on whether the earthquake was generated in the crust in an inelastic or elastic medium. These results suggested a PGV maximum roughly corresponding to the 10^{-7} PGV values from the DOE PSHA (Figure 3-1).

The second area of research in Hanks et al (2013) was to examine all the potential geologic indicators of unexceeded ground motion (UGM). These are expressed as the ages of fragile geologic structures that have survived in the absence of some level of ground shaking. The idea is that if these ground motions occurred in the past, they would have damaged or even destroyed these features. At Yucca Mountain, Hanks et al. (2013) identified two classes of such fragile geologic structures: the lithophysal units of the Topopah Spring Tuff, which is the repository host horizon, and precariously balanced rocks (PBRs) on the west face of Yucca Mountain.

Lithophysae are cavities (bubbles) that form in volcanic tuffs as a result of the volcanic gases exsolved during initial tuff cooling. These cavities constitute approximately 10–30 percent of the rock mass volume in the repository host horizon. They tend to be roughly spherical, uniform in size and distribution, and small (1 to 10 cm in diameter). Laboratory strength tests of the lithophysal units were combined with numerical simulations to define strain thresholds and to predict levels of stress that would damage the lithophysae. Results of these analyses indicated that PGVs in the range of 1.7 to 3.2 m/s would result in significant damage to the lithophysae. Because such damage is not observed in the tuffs, Hanks et al. (2013) concluded that these levels of ground shaking have not occurred at Yucca Mountain since the units were first deposited and cooled 12.7 Ma. As shown in Figure 3-1, the range of these predicted unexceeded PGVs fall well below the mean of the CRWMS M&O (1998) hazard curve, with corresponding AEPs between 5×10^{-6} and 5×10^{-7}.

PBRs at Yucca Mountain are large free standing boulders that formed along the exposed cliffs of the densely welded, crystal-rich member of the Topopah Spring Tuff. They resulted from differential erosion of the tuff, and in their present configuration, many of these appear to be balanced on pedestals. Brune and Whitney (2000) first suggested that these rocks could be used to constrain ground motions at Yucca Mountain based on an estimate of the amplitude and frequency range of the ground motions necessary to topple or overturn them, and the length of time that these rocks have been in their precarious state. Purvance et al. (2009) developed detailed fragility analyses of the nine most prominent PBRs at Yucca Mountain. Results for six of these are shown in Figure 3-1 (the PBRs are named: Matt-Cubed, Len, Nichole, Tripod, and Whitney).

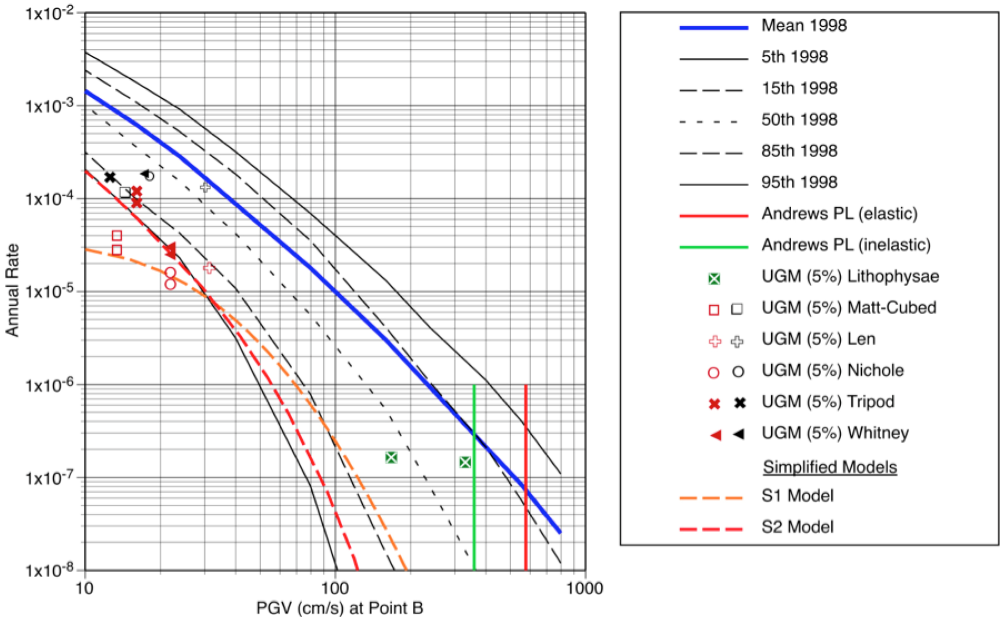

Figure 3-1. Graph summarizing the results from Hanks et al. (2013) plotted against the 1998 DOE PSHA results for Yucca Mountain. For the unexceeded ground motion results, the red symbols represent precarious balanced rocks ages based on the abundances of ^{36}Cl and black symbols represent the varnish microlamination ages, all taken to be 15 ka. This figure was adapted from Figure 46 Hanks et al. (2013).

The ground motions that would topple these rocks fall well below the predicted ground motion amplitudes based on the mean CRWMS M&O (1998) hazard curve. A picture of “Tripod” from Hanks et al (2013) is reproduced here in Figure 3-2 to provide a perspective of the nature and character of these precariously balanced rocks.

The third area of research in Hanks et al (2013) focused on how the advancements in ground motion characterization and ground motion modeling that have occurred since 1998 could impact the CRWMS M&O (1998) PSHA results. These advancements in ground motion modeling have taken place largely through the “Next Generation of Ground-Motion Attenuation Models” (NGA) program. NGA-West, and its follow-on NGA-West2, are multi-year, multidisciplinary research programs coordinated through the Pacific Earthquake Engineering Research Center (PEER), in partnership with the USGS and the Southern California Earthquake Center. The NGA research program benefited from the substantial increase in the number of strong motion recordings that have become available in the last 15 years, especially from the large set of recordings from Taiwan and Japan.

Perhaps the most significant advancement in the NGA models is the reduction of aleatory uncertainty. In the ground motion characterization for the 1998 DOE PSHA, the ground motion attenuation equations were developed based on a fully ergodic assumption. The ergodic assumption considers the spatial sample of observed ground motions across different regions to be equivalent to a time sample of ground motions generated at a single site by successive earthquakes. In other words, a collection of regional strong motion records from across a region provides the same statistical representation of the ground motion as an equal number of strong motion recordings at a single site accumulated over many years of recording. Under an ergodic assumption, the resulting ground motion

Figure 3-2. Photograph by Tom Hanks of the precariously balanced rock at Yucca Mountain named "Tripod." This figure was adapted from Figure 20 in Hanks et al. (2013).

prediction equations include significant aleatory variability, which is the main contributor to the extreme ground motions at low AEPs in the 2008 DOE PSHA. This is one of the reasons the mean hazard approaches the 95th fractile in the DOE hazard curve (Figure 2-1).

The large increase in the number of available strong motion records has allowed ground motion models produced by NGA-West and NGA-West2 to reduce or eliminate ergodicity in their models. The NGA models include specific terms to capture the site and path effects (e.g., Rodriguez-Marek et al. 2013). In effect, much of the aleatory variability is translated to epistemic uncertainty in the new site and path terms. This resulting shift in how the total uncertainty is partitioned among epistemic and aleatory components leads to a potentially significant reduction in the mean hazard at low AEPs. Hanks et al. (2013) developed two simplified PGV hazard models based on new NGA-West ground motion models (Power et al., 2008). Both of these simplified models, shown as S1 and S2 in Figure 3-1, predict significantly lower PGVs when compared to the DOE (2008) PSHA.

CNWRA staff evaluated the application of the NGA-West strong motion data to assess the issue of extremely large ground motions at low AEPs. The CNWRA analysis was based on a statistical study of aftershocks recorded following the 1999 Chi-Chi earthquake in Taiwan. The Chi-Chi aftershock data set was used for this study because it contained a wealth of available records. The statistical analysis developed in Huyse et al. (2010) by the CNWRA staff indicated that although the attenuation of PGA from source to receiver from these aftershocks generally followed a lognormal distribution, significant deviations from the lognormal model existed in the upper and lower tails of the distributions. In general, the study found that a standard lognormal attenuation equation overpredicted the expected number of very large PGA values—those that would fall within the tail of the lognormal distribution—compared to the number of observed very large PGA values. Huyse et al. (2010) showed that the distributions of the resulting ground motions in the tails are better characterized by extreme value distributions (more precisely, a generalized Pareto distribution). Although the generalized Pareto distribution pertains only to a small part of the overall distribution of ground motions, the difference between the lognormal and the generalized Pareto distribution is important because it is precisely this upper tail of the distribution that controls the estimate of ground motions at low AEPs. Results in Huyse et al. (2010) also show that, for small AEPs, the composite distribution model (lognormal over much of the distribution and generalized Pareto distribution in the tails) yields considerably lower PGA values at low AEPs than the unbounded lognormal distributions alone.

During the NRC review of the DOE Safety Evaluation Report, DOE provided an update to its seismic hazard curves at low AEPs to constrain the extreme ground motions based on some of the results from the physical limits and the observed geomechanical conditions of the near surface volcanic and sedimentary strata at Yucca Mountain. DOE referred to these two approaches as the shear-strain-threshold and the extreme-stress-drop at the seismic source methods (DOE, 2009). To implement the shear-strain-threshold method, DOE used laboratory rock mechanics data, corroborated by numerical modeling, to develop a shear strain threshold distribution. This distribution was incorporated into the seismic hazard using site-response calculations based on its random vibration theory equivalent linear model. To implement the extreme-stress-drop method, DOE convened a panel of experts that developed a distribution of extreme stress drops for the fault sources in the Yucca Mountain vicinity. The resulting expert distribution was based on stress drop measurements and apparent stresses from laboratory experiments. This distribution was mapped into a distribution of extreme ground motion for the reference rock outcrop through random vibration theory site-response modeling. The DOE conditioned hazard curves, which were based on a combination of the two methods, are shown in Figure 3-3. Of the two approaches, the extreme-stress-drop approach led to the more significant reduction in the hazard at low AEPs.

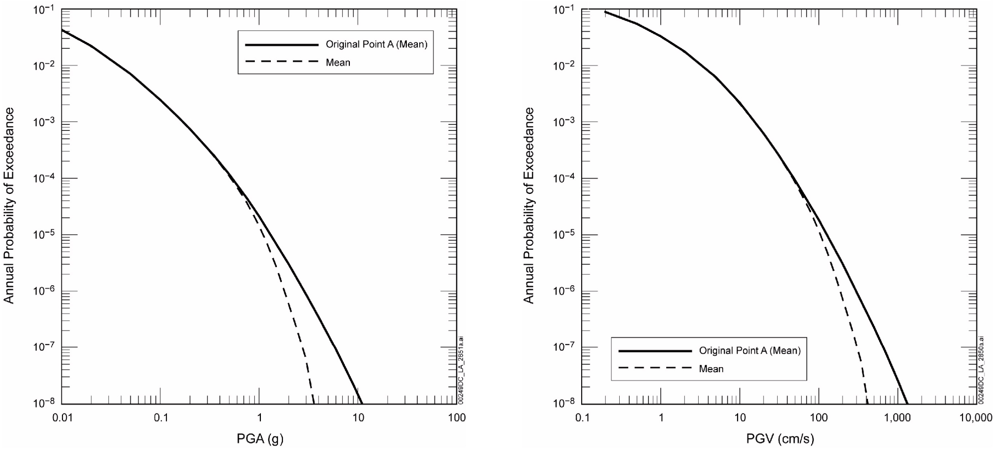

Figure 3-3. Conditioned and unconditioned reference rock outcrop mean peak ground acceleration and peak ground velocity curves based on the DOE conditioning methods. These figures were adapted from Figures 1.1-79 and 1.1-80 DOE (2009).

3.2 Evolution of the SSHAC Process

Since completion of the DOE PSHA (CRWMS M&O, 1998), the SSHAC process has been used extensively to develop new or updated PSHAs for nuclear and other critical facilities both in the United States and worldwide. These include site characterization studies for new power plant construction in South Africa; country-wide reassessments of seismic hazards in Switzerland, Spain (presently ongoing), Japan (presently ongoing), and Taiwan (presently ongoing); and region-wide assessment of seismic hazards for dam safety in British Columbia, Canada. In addition, an SSHAC Level-4 study was used to develop the updated probabilistic volcanic hazard assessment for Yucca Mountain.

SSHAC studies also have been used extensively across the United States to reevalaute the seismic hazards at all U.S nuclear power plants. Beginning in the early 2000s, interest grew on the part of the nuclear utilities in the United States to pursue early site permits and combined operating license applications for new nuclear power plants. In response, EPRI conducted a regional SSHAC Level-3 ground motion characterization study (EPRI, 2004) for central and eastern North America. This study was the first application of an SSHAC Level 3 process in the United States. The study was followed by a regional seismic source characterization study called the Central and Eastern United States Seismic Source Characterization (CEUS-SSC) Project, which is documented in NUREG–2115 (NRC, 2012a). This was also an SSHAC Level-3 study developed to provide a regional seismic source model for use in PSHAs for nuclear facilities. The study replaced previous regional seismic source models conducted for this purpose, including the EPRI-SOG and LLNL models.

The experiences gained from the implementation of the SSHAC process since the 1998 DOE PSHA led the NRC to develop practical implementation guidance, which is documented in NUREG–2117 (NRC, 2012b). The timing of this implementation guidance was advantageous, because in 2012, after the Great Tohoku earthquake and disaster at the Fukushima Dai-ichi nuclear power plant, the NRC issued a request for information to all operating commercial nuclear power reactors in the United States, pursuant to 10 CFR 50.54(f), to provide updated seismic hazard assessments. All the nuclear power plants in the central and eastern United States relied on the EPRI (2004) and NUREG–2115 models. The nuclear power plants in the western United States conducted site-specific source characterization studies, although Palo Verde Nuclear Generating Station and Diablo Canyon Power Plant worked together to develop a regional ground motion characterization model called the Southwestern United States (SWUS) ground motion model . All of these PSHAs were developed as SSAHC Level-3 studies.

The important organizational differences between SSHAC Level-3 and Level-4 studies are illustrated in Figure 3-4. The fundamental difference is how the technical experts interact to develop the logic trees. In a Level-3 study, the technical experts produce a single logic tree that captures the overall distribution agreed to by the technical evaluators through the process of challenge and defense. This process occurs throughout the duration of the project, but most intensely during the formal working meetings. The clear advantage of this approach is that the various proponent models also are vigorously debated by the technical integrators throughout the project, leading to a final seismic or ground motion characterization model that fully integrates the information.

In a Level-4 study, although the experts or expert teams interact at the workshops, the primary interactions, and the main form of technical challenge and defense, take place in the elicitation meetings between individual technical integrators and the Technical Facilitator Integrator. This means that there is significantly less interaction among the technical integrators. In a Level-4 study, each expert or expert team is charged with producing a logic tree reflecting their own view of the distribution that captures the center, body, and range of the technically defensible interpretations. The Technical Facilitator Integrator is then charged with aggregating these individual logic trees into the final integrated distribution. The simplest way of doing this, which will often be the default in a Level-4 study, is simply to combine the logic trees, with equal weighting, into a single overall logic tree. However, in a Level-4 study, the Technical Facilitator Integrator has the responsibility to justify the weights assigned within the aggregated distribution. NRC guidance in NUREG–2117 (NRC 2012b) still considers SSHAC Level-3 and Level-4 studies to provide equivalent regulatory assurance.

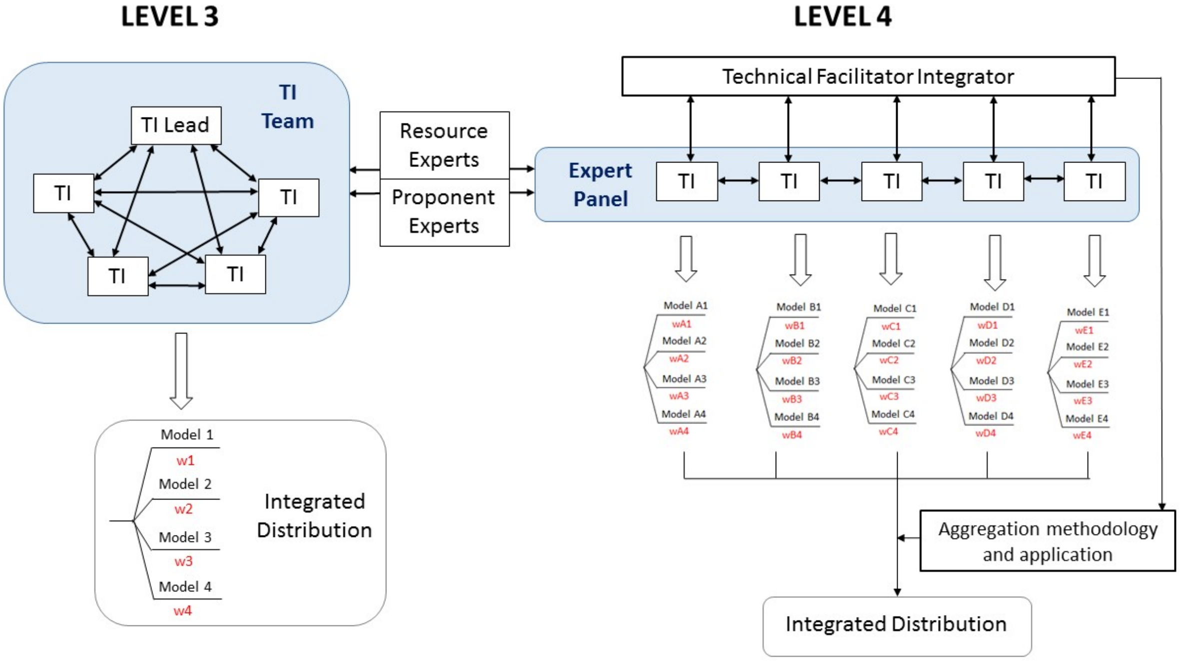

Figure 3-4. Organizational and structural differences between Level 3 and Level 4 studies. The role of the PPRP is identical in both cases and the same sequence of at least three formal workshops is also followed in both cases. This figure was adapted from current revision to the SSHAC implementation guidance (NUREG–2213, in press). TI is the technical integrator.

4 SUMMARY

DOE calculations of the seismic hazards for both preclosure and postclosure analyses in the Yucca Mountain repository license application were developed from a PSHA conducted by DOE nearly twenty years ago (CRWMS M&O, 1998). DOE followed guidance for the use of formalized expert judgment or expert elicitation that was being developed at the time by the SSHAC. The use of expert elicitation or expert judgment, and supporting guidance, was necessary because of the complexity in the tectonic environments at Yucca Mountain and the limited data available for seismic source and ground motion characterization. The resulting seismic hazard analysis is for a reference hard rock site. Following the development of the PSHA, DOE conducted site-response modeling to condition the PSHA results so they would be applicable to the surface facilities in Midway Valley and the repository drifts in the subsurface. The resulting repository-level and surface-level seismic hazard curves served as the primary inputs to the DOE postclosure performance assessment, surface and subsurface seismic design, and preclosure seismic risk assessment.

To prepare for the review of the DOE PSHA, the NRC and CNWRA staffs closely followed the development of the PSHA through the many PSHA project workshops and meetings. In addition, the CNWRA and NRC staffs developed review tools to support an efficient and effective review of the DOE license application. These included a detailed catalog or database of only those faults within 100 km of Yucca Mountain that could contribute to the seismic hazard (Type I Faults) and a computer program (3DStress) that would allow users to assess the potential seismic activity of theses faults based on their slip tendency. Development of these review tools assisted the CNWRA and NRC staff in identifying and focusing on only those faults in the Yucca Mountain region that could contribute to the seismic hazard. Staff also conducted a series of regional geological and geophysical investigations designed to develop a thorough understanding of the geologic and seismotectonic setting. These studies proved valuable in helping staff evaluate new and potentially controversial results that emerged at the time from the early application of GPS technology to seismic hazard studies.

One feature of the DOE PSHA results that drew considerable attention from the larger technical community after the results were published in 1998 was the very large ground motions indicated in the seismic hazard curves at very low AEPs. For example, the resulting PGAs at Yucca Mountain for the 10^{-6}, 10^{-7}, and 10^{-8} AEPs at the reference bedrock outcrop site are 3g, 6g, and 11g, respectively, and the resulting PGVs for the same AEPs are 3.0 m/s, 6.5 m/s, and 13.0 m/s. Research was conducted by the USGS to evaluate whether these very large ground motions are physically realizable. This research included a study to examine whether there was a physical limit to the amplitude of ground shaking based on the ultimate strength of the rocks and soil through with the seismic energy propagates. Results from this study suggested that the rock mass experiencing the intensity of PGVs indicated by the DOE hazard curve at low AEPs would deform and dissipate the seismic energy rather than maintaining their elastic properties. The USGS also evaluated the fragility of geologic structures that appeared to have survived in the absence of high levels of ground shaking. These fragile structures include the lithophysal units of the Topopah Spring Tuff and precariously balanced boulders and rock columns on the west face of Yucca Mountain. These structures provide a record of the level of unexceeded ground motions since the time the structures formed (late Quaternary in the case of the precariously balanced rocks and 12.7 Ma for the Topopah Spring Tuff). Finally, the USGS re-evaluated the potential seismic hazard based on more modern ground motion prediction equations, developed as part of the NGA-West and NGA-West2 projects. These updated ground motion prediction equations reduce or eliminate ergodicity in their models, which reduces the overall aleatory variability in the ground motion models. The large aleatory variability was cited as one of the main reasons the DOE 1998 hazard curves indicated such large ground motions at low AEPs. CNWRA staff also evaluated the potential causes of the extreme ground motions by testing whether a composite lognormal and generalized Pareto distribution is better fitted to ground motion attenuation data than a simple unbounded lognormal distribution. Results from the USGS and CNWRA studies indicated that the original DOE hazard curve is conservative at AEPs below approximately 10^{-6}. In an update to the Safety Analysis Report, DOE developed conditioned seismic hazard curves, based in part on the USGS research, to account for large ground motions at low AEPs.

Finally, during the development of the Safety Evaluation Report (SER) there were significant developments in how the SSHAC principles are administered, based on the lessons learned from many recent applications of the SSHAC process used to update the seismic hazards at U.S. and international power plants following the 2011 Great Tohoku earthquake and resulting disaster at the Fukushima Dai-ichi nuclear power plant. Most notably, all recent (and on-going) seismic hazard studies at nuclear power plants have used an SSHAC Level-3 study. The DOE 1998 PSHA was a SSHAC Level-4 study. NRC guidance in NUREG–2117 (NRC 2012b) still considers SSHAC Level-3 and Level-4 studies to provide equivalent regulatory assurance. In this context, regulatory assurance refers to the confidence by the NRC staff that the data, models, and methods of the larger technical community were properly considered and that the center, body, and range of technically defensible interpretations were appropriately represented and documented in the resulting PSHA.

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